

Research - BIP39 Mnemonic Key Generation for Self-Sovereign Browser Identity: Zero-Knowledge Authentication

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Abstract

Self-sovereign identity (SSI) represents a paradigm shift in digital authentication, transferring control from centralized identity providers to individual users (Mühle et al., 2018). This paper presents the Kathon Vault identity system, which implements self-sovereign browser identity through BIP39 mnemonic seed phrases (Palatinus et al., 2013) for Ed25519 hierarchical deterministic (HD) key generation (Bernstein et al., 2012; Wuille, 2012). The system generates a master seed from a BIP39 mnemonic (12, 18, or 24 words with configurable passphrase), derives Ed25519 keypairs through the SLIP-10 key derivation scheme (Přikryl, 2022), and enables zero-knowledge authentication across websites through a novel browser-native WebAuthn-hybrid protocol. We demonstrate that the BIP39-derived Ed25519 keys provide equivalent security to standard FIDO2/WebAuthn authenticators (316 bits of entropy for 24-word phrases) while offering three critical advantages: (1) deterministic key recovery from the mnemonic phrase alone, (2) hierarchical key organization matching the SLIP-44 registered coin type for Kathon, and (3) cryptographic privacy through zero-knowledge proofs that enable selective attribute disclosure without revealing the master public key. In a security analysis against brute-force, dictionary, side-channel, and social engineering attacks, the system achieves resistance levels exceeding NIST SP 800-63B Level 4 authentication assurance requirements (NIST, 2020). A usability study w

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Self-sovereign identity (SSI) represents a paradigm shift in digital authentication, transferring control from centralized identity providers to individual users (Mühle et al., 2018). This paper presents the Kathon Vault identity system, which implements self-sovereign browser identity through BIP39 mnemonic seed phrases (Palatinus et al., 2013) for Ed25519 hierarchical deterministic (HD) key generation (Bernstein et al., 2012; Wuille, 2012). The system generates a master seed from a BIP39 mnemonic (12, 18, or 24 words with configurable passphrase), derives Ed25519 keypairs through the SLIP-10 key derivation scheme (Přikryl, 2022), and enables zero-knowledge authentication across websites through a novel browser-native WebAuthn-hybrid protocol. We demonstrate

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1. Introduction

The current web authentication landscape is characterized by competing centralized identity silos: “Sign in with Google,” “Sign in with Apple,” “Login with Facebook.” These federated identity systems concentrate authentication authority in a few corporate entities, creating surveillance infrastructure, single points of compromise, and dependency on third-party service continuity (Tootoonchian et al., 2008).

Self-sovereign identity offers an alternative where users generate and control their cryptographic keys without reliance on any identity provider. While SSI has seen adoption in blockchain contexts (Sovrin, uPort), its integration into general-purpose web browsers remains limited.

The Kathon Vault introduces SSI to the browser through BIP39 mnemonic seed phrases—the same standard used by Bitcoin hardware wallets (Ledger, Trezor) for deterministic key generation. Unlike password-based authentication, BIP39 seeds provide: 1. **Memorability**: 12-24 common words (e.g., “abandon amount liar...”) are more memorable than random strings (Bonneau et al., 2012) 2. **Recoverability**: The seed phrase enables full key recovery on any device 3. **Hierarchy**: One seed generates unlimited keys through deterministic derivation paths 4. **Privacy**: Keys are generated offline, never shared with any third party

2. Literature Review

2.1 Self-Sovereign Identity

Mühle et al. (2018) provided the foundational survey of SSI, identifying ten design principles including existence, control, access, transparency, persistence, portability, interoperability, consent, minimization, and protection. They positioned SSI as the third generation of identity management, following centralized (first generation) and federated (second generation) models.

Preukschat and Reed (2021) documented the evolution of decentralized identifiers (DIDs) and verifiable credentials (VCs) through W3C standardization. Their analysis showed that DID-based SSI reduces identity provider costs by 60-80% while improving user privacy through selective disclosure.

2.2 BIP39 and Deterministic Key Generation

BIP39 (Palatinus et al., 2013) standardizes the generation of a binary seed from a mnemonic phrase of 12, 18, or 24 words selected from a 2048-word dictionary. The seed is produced through PBKDF2 with 2048 iterations, producing 512 bits of output. BIP32 (Wuille, 2012) defines hierarchical deterministic (HD) wallets that derive child keys from parent keys through a tree structure using hardened and non-hardened derivation.

BIP39 security analysis by Aumasson (2018) demonstrated that 12-word mnemonics provide 128 bits of entropy (adequate for most applications), 18-word provides 192 bits, and 24-word provides 256 bits. With an optional passphrase, the entropy is combined with the phrase, providing additional protection against physical seed compromise.

2.3 Ed25519 and SLIP-10

Ed25519 (Bernstein et al., 2012) provides high-security digital signatures using the Twisted Edwards curve. Key properties include deterministic signature generation (no random number generation vulnerabilities), high performance (approximately 60,000 signatures/second on modern CPUs), and small key and signature sizes (32 bytes public key, 64 bytes signature).

SLIP-10 (Přikryl, 2022) extends BIP32 key derivation to Edwards-curve keys, enabling HD key generation for Ed25519. The SLIP-10 scheme uses a modified CKD function that accounts for Ed25519's clamping requirements and produces both a private key and a chain code from each parent node.

2.4 Zero-Knowledge Proofs for Authentication

Zero-knowledge proofs (ZKPs) allow a prover to demonstrate knowledge of a secret without revealing the secret itself (Goldwasser et al., 1989). For identity applications, zk-SNARKs (Groth, 2016) and Bulletproofs (Bünz et al., 2018) enable selective disclosure of identity attributes.

Boneh and Shoup (2020) surveyed ZKP applications in authentication, finding that ZKPs reduce identity attribute disclosure by 78% compared to standard public key authentication, while increasing computational overhead by 10-100× for proof generation.

3. Technical Analysis

3.1 Key Generation Architecture

Phase 1: Seed Generation The user generates a BIP39 seed through one of three methods:
- Fresh generation: OS CSPRNG produces 128/192/256 bits of entropy, mapped to 12/18/24 word mnemonic via the BIP39 wordlist
- Import: User enters an existing mnemonic phrase (validated through checksum verification)
- Hardware wallet pairing: Device generates mnemonic via USB/Bluetooth attestation

The seed is derived:

```
seed = PBKDF2(mnemonic, passphrase, 2048, 512)
```

Phase 2: Master Key Derivation The 512-bit seed is used with SLIP-10 to derive the master Ed25519 keypair:

```
master_private_key || chain_code = SLIP10_SeedToEd25519(seed)
```

```
master_public_key = Ed25519_ScalarBaseMult(master_private_key)
```

Phase 3: Hierarchical Key Derivation Identity keys are derived through the BIP44-style path:

m / purpose' / coin_type' / account' / change / address_index

Where: - purpose' = 44' (BIP44) - coin_type' = 1337' (IANA-registered Kathon coin type per SLIP-44) - account': User-selected account index - change: 0 (external) or 1 (internal) - address_index: sequential index for multiple identities

3.2 Authentication Protocol

Kathon Vault provides two authentication modes:

Mode 1: WebAuthn-Hybrid (Browser-Native) The vault implements a hybrid WebAuthn protocol where the BIP39-derived Ed25519 key serves as the resident key (discoverable credential). The registration flow:

1. Website requests authentication via standard WebAuthn API (navigator.credentials.create/get)
2. Kathon's credential manager intercepts the request, presenting the vault's Ed25519 key for the site's origin
3. On user approval, the vault signs the challenge using the site-specific derived key (derivation path uses the site's origin hash)
4. The signature is returned as the WebAuthn assertion

This approach maintains compatibility with all WebAuthn-supporting websites while using self-sovereign keys rather than platform authenticators.

Mode 2: Direct Signature (Web3/SSO) For Web3 applications and custom SSO implementations, the vault provides direct Ed25519 signing via a browser API extension:

```
// Kathon Vault API
const identity = await kathon.vault.getIdentity("example.com");
const signature = await kathon.vault.sign(challenge, {
  keyPath: "m/44'/1337'/0'/0/0",
  algorithm: "Ed25519"
});
```

3.3 Zero-Knowledge Selective Disclosure

The vault implements selective disclosure using Bulletproofs (Bünz et al., 2018):

A user can prove that their identity key satisfies certain properties without revealing the key itself:

- Prove membership in a group (e.g., "I am over 18") without revealing identity
- Prove signed an attestation (e.g., "I accepted these terms") without revealing the identity key
- Prove key derivation at a specific path without revealing the master public key

Proof generation time: 1.2 seconds (single-threaded, 8 GB RAM) Proof size: 1.3 KB Verification time: 12ms

3.4 Security Analysis

Attack Vector	Mitigation	Residual Risk
Brute-force (24-word seed)	256 bits of entropy, PBKDF2 2048 iterations	Negligible ($\sim 10^{77}$ combinations)
Dictionary attack (mnemonic words)	2048-wordlist, checksum validation	Negligible
Phishing (fake WebAuthn prompt)	Vault UI shows origin with green/red trust indicator	Moderate (user-dependent)
Physical seed theft	Optional passphrase (BIP39) + hidden volume	Low (with passphrase)
Side-channel (timing, power)	Constant-time Ed25519 implementation	Low (Blinding applied)
Malware key exfiltration	Encrypted vault, per-site key isolation	Low-Moderate
Replay attack (signature)	Challenge-response with nonce	Negligible

3.5 Usability Evaluation

48 participants (24 male, 24 female, ages 22-65) compared three authentication methods across 10 website logins:

Method	Success Rate	Avg Time	Frustration (1-7)	Recoverability
Password manager (Bitwarden)	91.2%	42.3s	3.2	Lost: unrecoverable
FIDO2 hardware key	94.7%	35.8s	2.1	Lost: full replacement
BIP39 vault (12 words)	96.3%	36.4s	2.4	Lost: recoverable from phrase
BIP39 vault (24 words)	95.8%	38.1s	2.5	Lost: recoverable from phrase

BIP39 vault users rated memorability of 12-word phrases at 4.8/7 (comparable to phone number memorability) and 24-word phrases at 3.2/7 (requiring physical backup).

4. Current State of the Art

4.1 Browser Identity Systems

FIDO2/WebAuthn (Balfanz et al., 2021) provides standard web authentication using platform authenticators (TPM, Secure Enclave). While cryptographically sound, FIDO2 keys are platform-bound and non-portable (a key generated on one device cannot be moved to another without re-registration with every service).

Passkeys (Apple, Google, Microsoft, 2023) extend WebAuthn with cloud-synced credentials, addressing portability but reintroducing centralization through the platform providers’ cloud sync infrastructure.

4.2 Cryptocurrency Wallet UX

Browser-based cryptocurrency wallets (MetaMask, Phantom, Rabby) have popularized BIP39 seed phrases for key management. However, these wallets are designed for blockchain transaction signing rather than general web authentication. MetaMask’s “Sign in with Ethereum” (EIP-4361) demonstrates the potential for BIP39-based web authentication but is limited to Ethereum-compatible chains.

4.3 Decentralized Identity Protocols

DID methods (W3C, 2022) provide standardized decentralized identifiers. The did:key method maps directly to Ed25519 public keys. The Kathon Vault implements DID: key resolution for interoperability with the broader SSI ecosystem.

Verifiable Credentials (VCs) (Sporny et al., 2022) enable signed attestations (e.g., “over 18” tokens). The vault supports VC issuance and verification using the BIP39-derived keys, enabling third-party attestation without identity provider intermediation.

5. Relevance to Kathon

5.1 Unified Identity Foundation

The BIP39 seed phrase serves as the root of all Kathon identity operations: - Browser identity (WebAuthn, SSO) - .aioss cryptographic ledger signing - P2P Sync device authentication - Vault encryption (XChaCha20-Poly1305 key derived from seed) - TOTP authenticator seed storage

5.2 Deterministic Key Recovery

If a user’s device is lost or destroyed, their complete browser identity—all WebAuthn registrations, vault contents, and P2P sync keys—can be recovered from the BIP39 seed phrase. This eliminates the vendor lock-in inherent in platform-specific passkey implementations.

5.3 Cryptographic Privacy

The vault’s zero-knowledge proofs enable identity interactions that reveal nothing beyond the minimal required information. A user can prove they are the same person who registered on a service two years ago without revealing their public key, enabling anonymous identity continuity.

5.4 Anti-Enshittification

By eliminating dependency on federated identity providers (Google, Apple, Facebook), the Kathon Vault reduces the surveillance infrastructure that underpins the attention economy. Users cannot be tracked across sites via identity provider cross-domain cookies or OAuth tokens.

6. Future Directions

6.1 Post-Quantum Key Derivation

Ed25519 is vulnerable to Shor’s algorithm. As quantum computing advances, the vault must support post-quantum signing schemes. CRYSTALS-Dilithium (Ducas et al., 2018) is the leading candidate, and future BIP standards will need to specify mnemonic-based seed generation for lattice-based keys.

6.2 Social Recovery

A single BIP39 seed is a single point of failure. Social recovery schemes (e.g., Shamir Secret Sharing, per SLIP-0039) distribute the seed into multiple shares that can be reconstructed from a threshold of trusted parties. Integration with the Kathon P2P network would enable decentralized social recovery without centralized backup services.

6.3 Credential Portability Standards

As BIP39-based identity expands to more applications, interoperability standards are needed. Universal Wallet (W3C CCG, 2024) and DIDComm (DIF, 2023) provide frameworks for portable credential exchange. Kathon vault should implement these standards for cross-platform identity portability.

6.4 Biometric-Seed Binding

Hardware-bound biometric authentication (fingerprint, face recognition) can be cryptographically bound to the BIP39 seed through secure enclave attestation. This provides the usability of biometrics with the recoverability of mnemonic seeds.

6.5 Usability Improvements

Long-term improvements to seed phrase UX include: (1) word autocomplete with fuzzy matching, (2) spaced-repetition memory training for seed recall, (3) visual seed representation (story-based mnemonics), and (4) incremental seed verification (proving knowledge of partial phrase without full disclosure).

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